Information Fusion 21 (2015) 159–172

Contents lists available at SciVerse ScienceDirect

Information Fusion

journal homepage: www.elsevier.com/locate/inffus

Fusing uncertain knowledge and evidence for maritime situational awareness via Markov Logic Networks

Lauro Snidaro [a], Ingrid Visentini [b,*], Karna Bryan [b]

[a] University of Udine, Department of Mathematics and Computer Science, Via Margreth 3, 33100 Udine, Italy
[b] NATO STO Centre for Maritime Research and Experimentation, Viale San Bartolomeo 400, 19126 La Spezia, Italy

ARTICLE INFO

Article history:
Available online 18 May 2013

Keywords:
Context-based fusion
Situational awareness
Uncertainty management
Markov Logic Networks

ABSTRACT

The concepts of event and anomaly are important building blocks for developing a situational picture of the observed environment. We here relate these concepts to the JDL fusion model and demonstrate the power of Markov Logic Networks (MLNs) for encoding uncertain knowledge and compute inferences according to observed evidence. MLNs combine the expressive power of first-order logic and the probabilistic uncertainty management of Markov networks. Within this framework, different types of knowledge (e.g. a priori, contextual) with associated uncertainty can be fused together for situation assessment by expressing unobservable complex events as a logical combination of simpler evidences. We also develop a mechanism to evaluate the level of completion of complex events and show how, along with event probability, it could provide additional useful information to the operator. Examples are demonstrated on two maritime scenarios of rules for event and anomaly detection.

1. Introduction

State-of-the-art situation assessment (SA) systems (e.g. an automatic surveillance system [1]) are able to deal with vast amounts of data and information also of a heterogeneous kind. Their goal is to provide a constantly updated situational picture about the observed environment or set of entities to an operator in order to facilitate human decision making. Updating the current system representation of the situation is generally performed by acquiring, through sensors or other sources of information, new observations which provide a possibly incomplete and uncertain view.

Currently, low-level sensory data is the main source of information used to understand the observed evolving scenario and to identify anomalous conditions; in particular, up to now maritime surveillance heavily relies on the Automatic Identification System (AIS), coastal radars, space-based imagery, and other sensors, to form a picture in which the operator can recognize complex patterns and make decisions [2,3].

Anomaly detectors or event recognition systems for maritime situational awareness are presented in [4,2,5–10]. The common thread that unites these works is the definition of an expert system, that aims at detecting a set of anomalous behaviours or potential threats. Subject matter experts define a knowledge base (KB), which comprises the possible abnormal patterns the target could follow; then, on the top of it, a reasoning engine queries the occurrence of an anomaly for a target object in an arbitrary time instant. For example, in [2] AIS data is used for extracting statistical behaviours of motion patterns, while in [5] situational awareness is achieved fusing knowledge-based detection with data-driven anomaly detection. In [4] a comprehensive literature survey of the anomaly detection process via data analysis is presented; definitions of anomaly and normalcy, explored under the light of decision making systems, are given in order to support the analytical reasoning process.

The main goal of a reasoning engine or probabilistic inference system is to associate a posterior probability distribution to a set of queries [11], given observed evidence. The incorporation of abductive/inductive and deductive inferencing processes is a vital element in an automatic fusion system, and it represents a fundamental step for situational awareness. How this involvement can be obtained, on both theoretical and applicative levels, is a crucial point, and is subject of ongoing research [12].

The reasoner is usually fired by low-level observations provided by sensors, covering in this way the majority of abnormal situations in the domain; however, it is interesting to notice how anomalous behaviours do not always follow standard trends or well-known patterns, especially if related solely to vessels movements, but sometimes they take the form of seemingly unrelated activities on a larger scale [13]. Ship-centric focus should be replaced by a broader vision, where the ideal situational awareness system

* Corresponding author.
E-mail addresses: lauro.snidaro@uniud.it (L. Snidaro), visentini@cmre.nato.int (I. Visentini).

http://dx.doi.org/10.1016/j.inffus.2013.03.004

should then be flexible and adaptive enough to integrate both low-level and high-level information (see Fig. 1), detecting anomalous or suspicious conditions by reasoning on manifest or uncertain data, but also on (apparently irrelevant) relations among objects, which may reveal unobserved coincidences. The maritime domain is a daunting scenario for testing such systems, because of many factors: its challenging nature where the coverage of wide areas is given by discontinuous and intermittent sensory data, its well-known commercial policies and practices which can suggest normalcy behaviour patterns, the presence of local contextual information, stable in time, which can depict alternative indicators of multi-layered situations, and the urgency for systems capable to provide effective and advanced warning to promote countermeasures to illicit activities.

The integration of contextual knowledge, as demonstrated in [14–16] where it is exploited for improving tracking accuracy, can greatly enhance the performance of an awareness system. Despite its value, the representation and use of context is often poorly integrated, if not absent, even if the richness and completeness of this information is extremely useful to properly interpret the available stream of raw sensor data from a multitude of points of view (security, safety, economical or environmental situation, etc.). Qualitative high-level knowledge can help to infer about hidden states from low-level data generated by sensors, other fusion processes or human reports. In other words, context is a powerful means to picture a broader and deeper operational situation, as it can reduce uncertainties where normally analysts would need to be consulted.

In this paper, we exploit MLNs to encode uncertain knowledge, fuse data coming from multiple (and possibly heterogeneous) sources, and perform reasoning on incomplete data. One key point of using the MLNs for reasoning is their ability to reason with incomplete or missing evidence, which is a crucial feature hardly found in other approaches, but sought after especially in the maritime domain, where the data is often inaccurate, delayed or simply not available. Another advantage with respect to other systems, is the fact that MLNs support inconsistencies or contradictions in the knowledge base, which is a problem when different experts provide contributes to it. This avoids non-trivial knowledge engineering techniques to be performed in order to guarantee rules consistency. Here we use Markov Logic Networks (MLNs) to detect two possible anomalous conditions in maritime domain, a rendezvous at sea and a hazardous combination of cargo ships in a harbour.

We use exemplary scenarios, the first one derived from experts' suggestions gathered at the NATO STO Centre for Maritime Research and Experimentation and the second one expanded from [17], to highlight how unobserved complex events could be built by logical combination of simpler evidence, and how contextual information is extremely valuable in many conditions. MLNs present advantages suited to our domain as they support reasoning with missing or partial observations (incomplete evidence), they allow to encode expert rules and relational knowledge with an associated degree of uncertainty, they are able to handle contradictions and inconsistencies [18].

Preliminary investigation on MLNs in maritime domain has been initiated in [19], where we leveraged the expressive power of first-order logic (FOL) and the probabilistic uncertainty management of Markov networks in order to detect anomalies via reasoning on uncertain knowledge. Here we aim to expand and refine that work by providing contributions for:

- clarifying the concepts of event (simple and complex) and anomaly in the scope of fusion terminology;
- explicitly explaining how simple and complex events can be encoded in the form of FOL formulas with associated degree of uncertainty in maritime domain;
- demonstrating how MLNs could provide a powerful tool for fusing heterogeneous sources (e.g. a priori, contextual, sensory, etc.) of information for situation assessment by being able to express unobserved complex events by logical combination of simpler evidences;
- developing a mechanism to evaluate the level of completion of complex events as this calculation is not directly solvable within the MLNs framework.

1.1. Terminology

To facilitate human decision making, an updated situational picture of the observed environment assessing the current state of domain entities and their relationships is required. Events and anomalies can be considered fundamental building blocks for developing such a picture of the environment. In this section, we provide the necessary definitions of these concepts and relate them to the JDL fusion model [12]. In the following, the term *level* will be used as per JDL terminology.

While there are many papers in the literature that deal with events and provide various definitions [20], we here break-down the main concepts in light of the typical functionality and requirements of a SA system. An event modelling framework in maritime domain was recently presented in [21], where a piracy example is presented with the intent of facilitating the decision making process, but no reasoner is associated to the graphical representation of events.

For our purposes an **event** is a "significant occurrence or happening". It can be subdivided in *simple*, when we consider the variation of a quantity or state, or *complex*, which is a combination of atomic or complex activities [20]. Fig. 2 gives an intuitive representation of the idea.

A **simple event**, is any significant variation of input data, at any level, discernible by the system. Also called *atomic* in the literature, we here use the term *simple* to avoid confusion with *ground atoms* defined in Section 2. They can be directly observable or not, and can be either instantaneous or last for an arbitrarily long period of time. As the name implies, this is the most basic type of occurrence and cannot be further decomposed into simpler constituting events.

More in general, variations of input signals (Level 0), of a target's state (e.g. speed, direction, etc. that can be included in Level 1), of a target's relation with other entities (Level 2), are all examples of simple events.

Complex events are a combination of two or more component events (simple or complex) that can be arbitrarily combined through logical operators ($\wedge, \vee, \neg$) to encode articulated expert and domain knowledge. Complex events can be either triggered by a specific time-ordered sequence of component events, or be

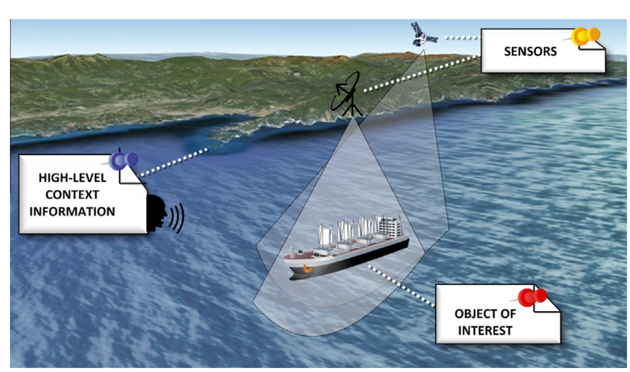

Fig. 1. Illustration of an ideal maritime situational awareness situation. The sensory data for an object of interest must be coupled by high-level contextual information.